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NEUTRINO EMISSION, MASS LOSS, AND THE
FREQUENCY OF SUPERNOVAE

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ABSTRACT

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Without steady mass loss during the red giant phase, most stars with mass above the Chandrasekhar limit should evolve into type II supernovae, but the predicted number of supernovae is much larger than the observed number. Although mass loss considerably lowers the predicted number, its effect will be reduced because of neutrino emission which decreases the time scale of the late phases. However, by use of presently known rates of stellar evolution and mass ejection, it is shown that loss of mass with or without neutrino emission will roughly account for the observed number of type II supernovae. Thus neutrino emission is not contradicted by observations of supernova frequency.

AUTHOR

INTRODUCTION

Against the current theory of progressive nucleosynthesis in stars (Burbidge, Burbidge, Fowler, and Hoyle 1957), is raised the serious objection that far more supernovae should be observed than is the actual case. For instance, on the assumption that every star with mass above the Chandrasekhar limit ($1.4 m_{\odot}$) gets rid of its excess mass by supernova explosion, we compute for the Galaxy with $\sim 2 \times 10^9$ stars of $m > 1.4 m_{\odot}$ and average lifetime $\sim 3 \times 10^9$ years (Schwarzschild 1958) a frequency of at least 200 supernovae per 300 years. This is too large by two orders of magnitude, compared with the observed frequency of about one supernova every 300 years (Zwicky 1958). This well-known result was obtained by Schwarzschild (1958) in two slightly different ways, using the death-rate function and the observed numbers of white dwarfs.

It is now apparent that many stars undergo extensive mass loss in the form of "winds" during the red giant phase of their evolution (Deutsch 1956a; Weymann 1962). This is believed to account for most of the excess mass that must be expelled. On the neutrino theory of late stellar evolution, however, the time scale is so shrunken that mass loss due to winds may be ineffective, and the neutrino

luminosity rises so high that energy requirements can force stars of relatively low mass to evolve to the supernova stage (e.g., Chiu 1961a,b). These considerations would lead us to expect again a higher frequency of supernova outbursts. It is the purpose of this paper to see whether the theory of neutrino emission is in conflict with observations.

EVOLUTIONARY TIME SCALES

Detailed stellar models have been computed for the late evolutionary phases only in the case of three masses $\geq 1.3 m_{\odot}$ (see Table 1 and references). Accordingly we list the three closest masses from the observed mass-spectrum relation tabulated by Schwarzschild (1958). The main sequence lifetime, τ_{ms} , is defined as the time required for a star to burn 13 percent of its hydrogen.

Hayashi and Cameron (1962a,b) and Hayashi, Hoshi, and Sugimoto (1962) have computed models for a star of $15.6 m_{\odot}$ as a red supergiant. The lifetime of carbon-burning is 2.3×10^5 years and of the laterphases, $\sim 6 \times 10^5$ years, without neutrino emission. These lifetimes are shortened to a total of at most 8×10^4 years if neutrino emission is included. Reeves (1962) also estimates that the time scale is reduced by a factor of 10 because of neutrino emission.

A star of intermediate mass ($4 M_{\odot}$) makes a brief excursion into the G and K giant region during helium-burning, but does not become a red supergiant until the onset of carbon-burning (Hayashi, Nishida, and Sugimoto 1962; Hayashi, Hoshi, and Sugimoto 1962). It spends 1×10^6 years burning carbon, and extrapolating from the results on the star of $15.6 M_{\odot}$, we estimate that it spends at least 3×10^6 years in the later phases. This number may be considerably underestimated, as degeneracy in the core will occur in the case of a star of $4 M_{\odot}$, whereas in the case of $15.6 M_{\odot}$ it is very slight. In fact, Hayashi, Nishida, and Sugimoto (1962) found that $\sim 4 M_{\odot}$ represents a critical mass below which degeneracy occurs in the core just before helium-burning. The red giant lifetime with neutrino emission included is 10^6 years (Hayashi, Hoshi, and Sugimoto 1962).

The evolutionary track of a star of $1.3 M_{\odot}$ enters the G - K red giant region during gravitational contraction and the onset of helium-burning. Degeneracy in the core raises the time scale to $\tau_{rg} > 2.5 \times 10^7$ years (Schwarzschild and Selberg 1962; Schwarzschild and Härm 1962). Presumably, after a brief period of non-degeneracy following the helium flash, the further evolution of the star is finally limited by renewed degeneracy, and the star becomes a white dwarf or type I supernova (population II and due to an entirely

different mechanism; see Hoyle and Fowler 1960) without returning to the red giant region. Plasma neutrino emission will have some effect on the luminosity of the core of the star, but not on the total luminosity (Chiu 1963b), and is therefore not believed to affect the time scale significantly.

Although the models for these three stars had different assumed initial chemical compositions, the time scales of evolution, especially during the later phases, should not be affected too much by a change in initial composition, at least to within the accuracy we require (cf. Table 1).

MASS LOSS

We now turn to the problem of mass loss by stars in the form of winds or ejection of shells. The solar wind carries away $3 \times 10^{-14} m_{\odot}$ /year, which is completely negligible (Parker 1963). Underhill (private communication) obtains observationally a mass loss of 10^{-6} to $10^{-7} m_{\odot}$ /year for Wolf-Rayet stars and believes that the normal O stars would have this rate reduced by a factor of 10. For a Be shell star ($10 m_{\odot}$), Underhill (1960) obtains $10^{-7} m_{\odot}$ /year, to be reduced by a similar factor for the normal B stars. Hence with main-sequence lifetimes of 5×10^6 and 1×10^8 years, respectively, the mass loss even from O and B stars is

negligible during the main-sequence phase of evolution.

During the red giant phase, however, observations show that mass loss can be considerable. Weymann (1962) obtains for α Orionis an outflow of $4 \times 10^{-6} m_{\odot}/\text{year}$. Allen (1955) gives for a star with its spectral type (M2 Iab) a mass of $\sim 20 m_{\odot}$. The corresponding escape velocity is consistent with the assumption of outflow of material. Deutsch (1956a) obtains a mass loss of $3 \times 10^{-8} m_{\odot}/\text{year}$ for α Herculis. This star is a visual binary with a computed mass of $15 m_{\odot}$ for the more massive M component. However, its spectral and luminosity class (M5 II) would indicate a mass more like $4 m_{\odot}$ (Allen 1955). Moreover, Weymann (1960) has pointed out that the interpreted velocity of outflow is not consistent with the escape velocity calculated for $15 m_{\odot}$. He uses Wilson's (1960) distance determination for α Herculis and inspection of the H-R diagram of galactic clusters to suggest that the mass of the M component is $\sim 4 m_{\odot}$. We adopt this mass in Table 1.

Hayashi, Hoshi, and Sugimoto (1962) found that the main effect of mass loss is to reduce the effective temperature. Now Deutsch (1960) showed that mass loss is vastly more efficient at the lower temperatures. Since stars with $m \geq 4 m_{\odot}$ spend less time in carbon-burning than in the later phases, the average rate of mass loss will be greater

than that indicated in Table 1. Moreover, Deutsch's value of the loss from α Herculis is a lower limit, and he points out that significant loss may even occur at the earlier spectral types, which would include part of the helium-burning phase of a star of $4 M_{\odot}$ (Deutsch 1960). Since the rate of loss should be roughly independent of stellar mass, perhaps Weymann's value is a better average. Therefore it seems that mass loss will be effective in reducing the mass of a star with initial $4 M_{\odot}$ to below the Chandrasekhar limit. The star will then become either a white dwarf with core composed of the products of carbon-burning or perhaps a supernova of type I. Table 1 also suggests that mass loss will be effective even up to $15 - 20 M_{\odot}$ (main sequence spectrum B2) for the case of no neutrino loss. Stars with $M < 4 M_{\odot}$ will almost certainly lose some mass, cool off, and avoid type II supernova explosion, with or without neutrino emission.

If mass loss is not efficient enough, however, ordinary evolutionary processes will make supernovae out of all stars with $M > 4 M_{\odot}$ (B8); with neutrino emission, mass loss will certainly be inefficient for the more massive stars because of the drastically reduced time scale, as indicated in Table 1 for $18 M_{\odot}$ (B2). So we shall regard $\sim B8$ as the critical spectral class for which earlier stars become

supernovae on the neutrino theory.

We note, parenthetically, that observations of globular and open clusters support the theoretical results that main-sequence stars evolve into red giants (at least the stars of low and intermediate mass). For the massive stars the evidence from OB clusters is suggestive (Hayashi and Cameron 1962a,b), even though not required (Chiu 1963a). Moreover, star-counts and the distribution of M giants in the field (Deutsch 1956b) support this view of evolution.

STELLAR STATISTICS AND FREQUENCY OF SUPERNOVAE

We must now estimate the number of O and B stars in the Galaxy. Roberts (1957) used Shnirelman's (1952) value of 1.8×10^6 B0-B5 stars to obtain 2.5×10^6 B0-B7 stars. Rubin et al. (1962) list 1440 O-B5 stars within a radius of 3 kpc around the sun; this value is estimated to be 5 percent complete. If we assume with Rubin et al. that the radius of the Galaxy is 15 kpc, we obtain a total of 7×10^5 O-B5 stars in the Galaxy. By extrapolation we get 1×10^6 O-B7 stars. Parenago (1948) and Roberts (1957) obtain 6×10^3 O stars in the Galaxy. Therefore we estimate that there are 5×10^4 O-B2 stars. Using the main-sequence lifetime of the latest star in a small spectral interval, we divide

the number of stars in the interval by τ_{ms} to obtain the predicted number of supernovae (SN). The cumulative spectral intervals and numbers of supernovae are listed in Table 2.

The observed frequency of both type I and type II supernovae in external galaxies is one in 300-400 years (Zwicky 1958). The uncertain completeness of the searches and intragalactic extinction indicates a true frequency that is higher by an unknown factor. The three, well-authenticated supernovae in our own Galaxy were of type I and show an apparent frequency of 1 SN/300 years. Other supernovae have been recorded in our Galaxy (Kukarkin, Parenago, Efremov, and Kholopov 1958), but their type is unknown. However, type II supernovae are known to be more common in general (Payne-Gaposchkin 1957). Hence we shall accept for our own Galaxy the "true" extragalactic rate of type II supernovae as > 1 SN/300 years.

We recall from the first paragraph of this paper that without mass loss the frequency of supernovae should be greater than 200 per 300 years. This is too large by about two orders of magnitude. From Table 2 we note that on the basis of mass loss with or without neutrino emission the predicted frequencies (despite the uncertainties in arriving at them) fall within a reasonable range of the observed frequency. In fact, if Payne-Gaposchkin's (1957) estimate of at least 8 type II SN/300 years in the Galaxy is correct,

the neutrino hypothesis improves the agreement.

Hence we conclude that the assumption of neutrino emission is at least not contradicted by observations of supernova frequency.

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TABLE 1
Stellar Lifetimes and Mass Loss
during the Red Giant Phase

M/M_{\odot}^*	Sp*	$\log \tau_{ms}^{\dagger}$ (yr)	$\log \tau_{rg}$ (yr) without ν -loss	$\log \tau_{rg}$ (yr) with ν -loss	$-dM/dt$ (M_{\odot}/yr) [‡]	References for τ_{rg}
18	B2	7.6	6.0	< 4.9	4×10^{-6}	1, 4
4	B8	8.4	> 6.6	6.0	$> 3 \times 10^{-8}$	2, 4
1.4	F1	9.6	> 7.4	> 7.4	...	3

* Observed mass-spectrum relation for the main sequence (Schwarzschild 1958, p. 277).

† Computed by Schwarzschild (1958, p. 277) as the time required to burn 13 percent of the hydrogen.

‡ Observed by Deutsch (1956) and Weymann (1962) for α Her ($\sim 4M_{\odot}$, Weymann 1960) and \propto Ori ($\sim 20M_{\odot}$), respectively.

1 Hayashi and Cameron (1962 a, b) for a star of $15.6M_{\odot}$.

2 Hayashi, Nishida, and Sugimoto (1962) for a star of $4M_{\odot}$.

3 Schwarzschild and Selberg (1962) and Schwarzschild and Härm (1962) for a star of $1.3M_{\odot}$.

4 Improved values of Hayashi, Hoshi, and Sugimoto (1962).

TABLE 2

Predicted Frequency of Supernovae
for Various Spectral Groups

Sp group	Number of Stars	$\log \tau_{\text{ms}} (\text{yr})$	SN/300 yr
O	6×10^3	6.6	0.5
O - B2	5×10^4	7.6	1
O - B5	$7-18 \times 10^5$	8.0	4-6
O - B7	$1-2.5 \times 10^6$	8.3	6-10